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VOLTAGE REFERENCE GENERATOR CIRCUIT USING LOW-BETA EFFECT OF A CMOS BIPOLAR TRANSISTOR

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CROSS-REFERENCE TO RELATED APPLICATION(S)

BACKGROUND

Field of the Invention

[1001] The present invention relates to generating a reference voltage in integrated circuits, and more particularly to reference voltage circuits for low-power applications.

Description of the Related Art

[1002] A bandgap reference circuit has improved temperature stability and is less dependent on power supply voltage than other known voltage reference circuits. Bandgap reference circuits typically generate a reference voltage approximately equal to the bandgap voltage of silicon extrapolated to zero degrees Kelvin, i.e., $V_{G0} = 1.205V$. Typical voltage reference circuits include a current mirror coupled to the power supply and the voltage reference node to provide a current proportional to the absolute temperature to the voltage reference node.

[1003] Integrated circuits having 3V power supplies can easily meet the demands of operating devices included in a cascoded current mirror and generate the reference voltage without compromising stability of the reference voltage. For example, a voltage reference generator with a power supply of 3V provides a reference voltage of 1.2V. The V_{DS} of a MOSFET included in the current mirror has a magnitude of $3V - 1.2V = 1.8V$, which is sufficient to operate the device under typical conditions with an acceptable power supply rejection ratio (PSRR) (i.e., the ability of the voltage

reference generator to reject noise on the power supply). However, as the power supply voltage drops, e.g., for low-power applications, available voltage headroom required to operate the devices included in the current mirror is reduced, the PSRR becomes more critical, and the voltage reference generator is less likely to provide a sufficiently stable reference voltage with respect to variations on the power supply.

[1004] Accordingly, improved techniques for generating stable reference voltages for low-power applications are desired.

SUMMARY

[1005] A voltage reference generator has been discovered that generates a stable reference voltage that is less than the bandgap voltage of silicon for power supply voltages less than 2V, yet provides sufficient voltage headroom to operate a current mirror. In one embodiment, the voltage reference generator has a power supply rejection ratio of at least 60dB and has improved noise performance as compared to traditional bandgap circuits. These advantages are achieved by leveraging the low-beta effect of a bipolar transistor formed in a CMOS process to generate a current proportional to an absolute temperature.

[1006] In some embodiments of the present invention, a voltage reference generator includes a bipolar transistor configured to amplify a base current of the bipolar transistor, the base current being proportional to an absolute temperature. The base current may be proportional to a voltage difference between two base-emitter voltages biased at different current densities, the voltage difference formed across a resistor coupled to the base of the bipolar transistor. A reference voltage produced by the voltage reference generator may be proportional to a parabolic function of temperature.

[1007] In some embodiments of the present invention, an integrated circuit includes a first bipolar transistor, a second bipolar transistor, and a resistor coupled to a base of the second bipolar transistor. A voltage difference between a base-emitter voltage of the first bipolar transistor and a base-emitter voltage of the second bipolar transistor forms across the resistor. A voltage reference node receives a voltage based at least in part on the voltage difference.

[1008] In some embodiments of the present invention, a method includes developing a base current of a first bipolar transistor. The base current is proportional to absolute temperature. The method includes amplifying the base current. The method includes generating a reference voltage based at least in part on the amplified base current. The base current may be proportional to a voltage difference between a base-emitter voltage of a second bipolar transistor and a base-emitter voltage of the first bipolar transistor. The voltage difference may be formed across a first resistor coupled to a base of the first bipolar transistor.

[1009] In some embodiments of the present invention, a method of manufacturing an integrated circuit includes forming a first bipolar transistor, a second bipolar transistor, and a resistor coupled to a base of the second bipolar transistor. A voltage difference between a base-emitter voltage of the first bipolar transistor and a base-emitter voltage of the second bipolar transistor forms across the resistor. The method includes forming a voltage reference node that receives a voltage based at least in part on the voltage difference.

BRIEF DESCRIPTION OF THE DRAWINGS

[1010] The present invention may be better understood, and its numerous objects, features, and advantages made apparent to those skilled in the art by referencing the accompanying drawings.

[1011] **FIG. 1** illustrates a voltage reference generator circuit.

[1012] **FIG. 2** illustrates a voltage reference generator circuit in accordance with some embodiments of the present invention.

[1013] **FIG. 3** illustrates a voltage reference generator circuit in accordance with some embodiments of the present invention.

[1014] The use of the same reference symbols in different drawings indicates similar or identical items.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

[1015] A typical voltage reference circuit (e.g., voltage reference generator 100 of FIG. 1) is designed to provide a temperature stable reference voltage (i.e., V_{REF}). In general, voltage reference circuits take advantage of two electrical characteristics to achieve the desired V_{REF} : the V_{BE} of a bipolar transistor is nearly complementary to absolute temperature, e.g., $V_{BE} = (-1.5\text{mV}/^\circ\text{K} \cdot T + 1.22)\text{V}$, and V_T is proportional to absolute temperature, i.e., $V_T = kT/q$.

[1016] A voltage proportional to absolute temperature (i.e., a ptat voltage) may be obtained by taking the difference between two V_{BE} s biased at different current densities:

$$\Delta V_{BE} = V_T \ln\left(\frac{J_1}{J_2}\right),$$

where J_1 and J_2 are saturation currents of corresponding bipolar transistors.

Accordingly, voltage reference circuit 100 includes a pair of pnp bipolar transistors (i.e., transistors 106 and 108) that are connected in a diode configuration (i.e., the collectors and bases of these transistors are coupled together) and coupled to ground. Transistor 108 has an area that is M times larger than the area of transistor 106. Thus, the saturation currents of transistor 108 and transistor 106 vary by a factor of M . The emitter of transistor 106 is coupled to an inverting input of operational amplifier 116. The emitter of transistor 108 is coupled, via resistor R_1 , to the non-inverting input of operational amplifier 116. Operational amplifier 116 maintains equivalent voltages at nodes 118 and 120, i.e., $V_{118} = V_{120} = V_{BE106}$. Hence, the difference between V_{BE106} and V_{BE108} (i.e., $\Delta V_{BE106,108}$) forms across resistor R_1 . Operational amplifier 116 and transistors 102 and 104 convert this voltage difference into a current (i.e., current I_1) proportional to the voltage difference:

$$I_1 = \frac{\Delta V_{BE106,108}}{NR_1} = \frac{V_T \ln\left(\frac{M}{N}\right)}{NR_1}$$

Since the thermal voltage V_T has a positive temperature coefficient of k/q , $k = 1.38 \cdot 10^{-23} \text{J/K}$ and $q = 1.6 \cdot 10^{-19} \text{C}$, the current proportional to the voltage difference is proportional to an absolute temperature, i.e., I_1 is a 'ptat' current.

[1017] Transistor 114 provides a voltage nearly complementary to absolute temperature (i.e., a 'ctat' voltage) because the V_{BE} of a bipolar transistor is nearly complementary to absolute temperature. By compensating the ptat current with a ctat voltage, transistors 102, 104, 106, 108, 112, and 114, and resistors R_1 and R_2 , may be appropriately sized to generate a particular reference voltage output having a zero temperature coefficient:

$$\frac{V_{REF} - V_{BE114}}{R_2} = PI_1;$$

$$V_{REF} = V_{BE114} + PI_1 R_2;$$

$$V_{REF} = V_{BE114} + \frac{PR_2 V_T \ln\left(\frac{M}{N}\right)}{NR_1};$$

$$\frac{dV_{REF}}{dT} = \frac{dV_{BE114}}{dT} + \frac{PR_2 k \ln\left(\frac{M}{N}\right)}{NR_1 q}.$$

Setting $\frac{dV_{REF}}{dT} = 0$, for V_{REF} to have a zero temperature coefficient,

$$\frac{PR_2 k \ln\left(\frac{M}{N}\right)}{NR_1 q} = -\frac{dV_{BE114}}{dT} = \frac{1.5mV}{^{\circ}K}.$$

$V_{BE114} = V_{BE106} = 0.74$ at $300^{\circ}K$ for an exemplary process and choosing $M = 8$, $N = \frac{1}{4}$, $P/N \sim 4$, and $R_2/R_1 \sim 1.2$:

$$V_{REF} = V_{BE114} + \frac{PR_2 V_T \ln\left(\frac{M}{N}\right)}{NR_1};$$

$$V_{REF} = 0.74V + \frac{1.5mV}{^{\circ}K} T;$$

at $300^{\circ}K$, $V_{REF} = 0.74V + 0.45V = 1.19V \approx 1.2V$.

V_{REF} is approximately equal to, $V_{G0} = 1.205V$, i.e., the bandgap voltage of silicon extrapolated to zero degrees Kelvin.

[1018] When the power supply is 3V, the V_{DS} of transistor 112 has a magnitude of $3V - 1.2V = 1.8V$, which is sufficient to operate the device to provide a current independent of fluctuations in V_{DS} . Thus power supply noise will have minimal effect on I_1 . However, for an exemplary low-power application, the power supply voltage is 1.62V. Voltage reference generator 100 provides only a V_{DS} of 0.42V for device 112. Transistor 112 may be operating in a linear/quasi-saturation current region and noise on the power supply will cause significant noise in PI_1 , thereby generating a noisy V_{REF} and degrading the accuracy of V_{REF} . The PSRR is typically determined empirically by presenting a varying signal on the power supply and measuring variations exhibited at the V_{REF} node. At a 1.62V power supply, voltage reference generator 100 is unable to provide a desired 60dB PSRR. The poor power supply rejection of voltage reference generator 100 makes voltage reference generator 100 inoperable for the purpose of providing a stable voltage reference. A desired voltage reference generator PSRR for a low-power application is at least 60dB over process and temperature variations. In addition, noise from operational amplifier 116, which dominates the circuit noise of voltage reference generator 100, is amplified by the current mirror thus amplifying noise on V_{REF} .

[1019] Referring to FIG. 2, voltage reference generator 200 improves the power supply rejection ratio and noise performance of voltage reference generator 100 by removing emitter resistor R_1 of voltage reference generator 100 and instead, including base resistor R_3 . Voltage reference circuit 200 includes a bipolar transistor (i.e., transistor 206) that is coupled in a diode configuration and coupled to ground. A second pnp bipolar transistor (i.e., transistor 208) is configured as an amplifier. Referring to FIG. 3, in another embodiment of the present invention, instead of coupling the base of transistor 206 to ground, transistor 206 may be coupled to node 330 and biased by transistors 332 and 334. Similarly, base resistor R_3 may be coupled to node 330 to receive the bias voltage generated by transistors 332 and 334.

[1020] Referring back to FIG. 2, transistor 208 has an area that is M times larger than the area of transistor 206. Thus, the saturation currents of transistor 208 and transistor 206 vary by a factor of M . The emitter of transistor 206 is coupled to an inverting input of operational amplifier 214. The emitter of transistor 208 is coupled to the non-inverting input of operational amplifier 214. Operational amplifier 214

maintains equivalent voltages at nodes 218 and 220, i.e., $V_{218} = V_{220} = V_{BE206}$. Hence, the difference between V_{BE206} and V_{BE208} , i.e., $\Delta V_{BE206,208}$, forms across resistor R_3 :

$$I_{B208} = \frac{V_{BE206} - V_{BE208}}{R_3} \text{ and}$$

$$I_2 = I_{E208} = (\beta_{208} + 1)I_{B208} = (\beta_{208} + 1) \frac{V_{BE206} - V_{BE208}}{R_3} = (\beta_{208} + 1) \frac{V_T \ln\left(\frac{M}{N}\right)}{R_3},$$

where $N = W_{204}/W_{202}$, W_{204} being the width of transistor 204 and W_{202} being the width of transistor 202 and the channel lengths of transistor 204 and transistor 202 being substantially equal. Since the thermal voltage V_T has a positive temperature coefficient k/q , the current proportional to the voltage difference is proportional to an absolute temperature, i.e., I_2 is a ptat current.

[1021] Transistor 212 provides a ctat voltage, V_{BE212} . By compensating the ptat current with a ctat voltage, transistors 202, 204, 206, 208, and 212, and resistors R_1 and R_2 , may be appropriately sized to generate a substantially constant reference voltage output, i.e., V_{REF} :

$$\frac{V_{REF} - V_{BE212}}{R_4} = I_2$$

$$V_{REF} = V_{BE212} + I_2 R_4$$

$$V_{REF} = V_{BE212} + (\beta_{208} + 1) \frac{R_4 V_T \ln\left(\frac{M}{N}\right)}{R_3}.$$

In other embodiments, a ctat current may be formed and summed with I_2 to create a substantially constant current. For a supply voltage of 1.62V and a target reference voltage of 0.96V, the following parameters are chosen: $M = 8$, $N = 1/4$, $R_3 = 16k\Omega$, $R_4 = 5.5k\Omega$. Note that the beta of a bipolar transistor has a dependence on temperature. In an exemplary process, the quantity $\beta+1$ is $(9.6 \cdot 10^{-3}T + 0.152)$ and V_{BE212} is $(-1.4 \cdot 10^{-3}T + 1.118)V$. Thus V_{REF} may be modeled as a quadratic function of temperature:

$$V_{REF} = aT^2 + bT + c,$$

where a, b, and c are greater than zero. In general, a, b, and c are determined according to target process technology, supply voltage, and reference voltage. Note that in a typical CMOS process, parasitic substrate pnp transistors (e.g., in the case of an n-well process) and parasitic substrate npn transistors (e.g., in the case of a p-well process) may be used as bipolar transistors. These transistors have a low-beta (e.g., $\beta < 10$) as compared to transistors formed in a bipolar process (e.g., $\beta > 100$). Thus currents produced by amplifying a base current of the CMOS bipolar transistor are manageable by typical CMOS devices.

[1022] Voltage reference generator 200 benefits from the low-beta of parasitic bipolar transistors by reducing noise on V_{REF} . In voltage reference generator 100, transistors 104 and 110 amplify the ptat current, i.e., current NI_1 is amplified by P/N, which is approximately 4, thus amplifying the noise contributions of the operational amplifier on V_{REF} . In voltage reference 200, the ptat current, i.e., current I_2 , is generated by amplifying the base current of transistor 208, which is a ptat current. Current I_2 itself is not amplified, thus the noise of the operational amplifier is not amplified and noise performance of voltage reference generator 200 is significantly improved as compared to voltage reference generator 100.

[1023] Although the reference voltage has a non-zero temperature coefficient, total variation of the reference voltage over the combination of variations in process and in temperature is less than for voltage reference generator 100. The effect on β of variations in process counteract the effect of variations in process on V_{BE} of the bipolar transistor and decreases the overall effect of process variations on voltage reference generator 200. The decrease in variations in V_{REF} for voltage reference generator 200 as a function of process is greater than the increase in variation as a function of temperature. Thus, voltage reference generator 200 has overall reduced variations in V_{REF} as compared to variations in V_{REF} for voltage reference generator 100 over process and temperature. At 1.62V, the PSRR of an exemplary voltage reference generator 200 is 60dB over all process and temperature conditions, and 70dB at nominal process and temperature conditions.

[1024] In some exemplary applications, it may be advantageous to generate a V_{REF} that varies with temperature. The ratio of R_4/R_3 may be adjusted to provide a slope appropriate to the typical application by strategically positioning the center of the parabola. For example, by appropriately positioning a vertex of the parabola, the slope of V_{REF} as a function of temperature may be adjusted to generate a V_{REF} that always increases or always decreases as a function of temperature under particular operating conditions. The exemplary embodiment of circuit 200 was designed for a supply voltage of 1.62V and a reference voltage of 0.96V, however, this circuit is not limited thereto. Voltage reference generator 200 may be operated at lower supply voltages and reference voltages, and remains operable so long as $V_{DD}-V_{REF} > 400\text{mV}$ (i.e., the current mirror remains operable).

[1025] While circuits and physical structures are generally presumed, it is well recognized that in modern semiconductor design and fabrication, physical structures and circuits may be embodied in computer readable descriptive form suitable for use in subsequent design, test, or fabrication stages. Accordingly, claims directed to traditional circuits or structures may, consistent with particular language thereof, read upon computer readable encodings and representations of same, whether embodied in media or combined with suitable reader facilities to allow fabrication, test, or design refinement of the corresponding circuits and/or structures. Structures and functionality presented as discrete components in the exemplary configurations may be implemented as a combined structure or component. The invention is contemplated to include circuits, systems of circuits, related methods, and computer-readable medium encodings of such circuits, systems, and methods, all as described herein, and as defined in the appended claims. As used herein, a computer readable medium includes at least disk, tape, or other magnetic, optical, semiconductor (e.g., flash memory cards, ROM), or electronic medium and a network, wireline, wireless or other communications medium.